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Fatigue load minimization in an operation of a wind farm

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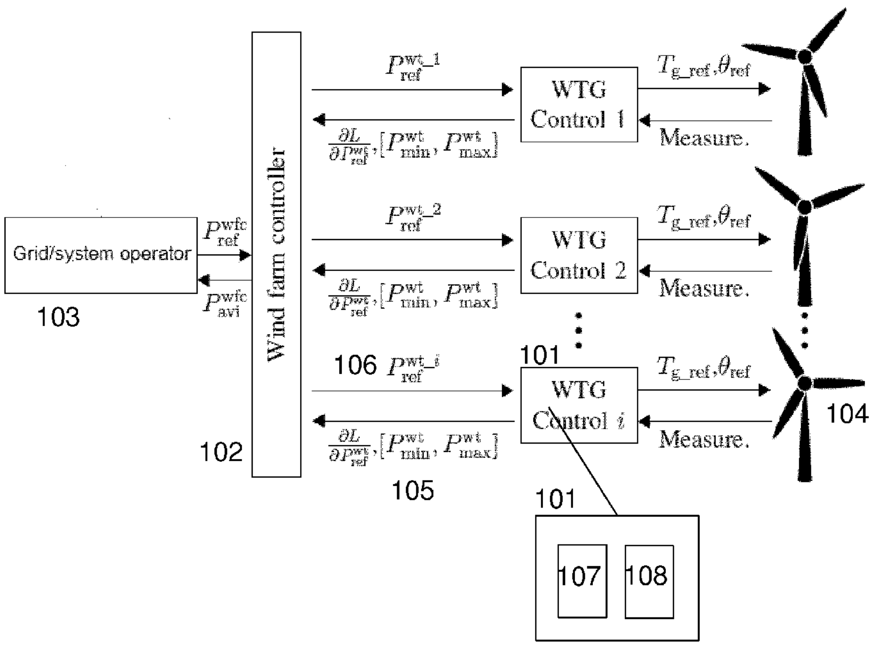

FIG. 1

(57) Abstract: The present disclosure relates to a method and system for controlling an operation of a wind farm connected to a grid, the wind farm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of: calculating a load sensitivity in the local controller of each wind turbine based on fluctuations of at least one fatigue load parameter of said wind turbine; providing an exchange signal between each of the local controllers and the central controller, said exchange signal comprising the calculated load sensitivity; solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines in the central controller based on the calculated load sensitivities of the wind turbines and power reference tracking provided by the grid, thereby providing local power references to each of the local controllers. The disclosure further relates to system for controlling an operation of a wind farm connected to a grid, the system comprising: at least one central controller

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comprising a central hardware processor and at least a first non-transitive, computer-readable storage device for storing instructions that, when executed by the central hardware processor, causes the at least one central hardware processor to perform the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines according to the disclosed method, thereby providing local power references to each of the local controllers; and local controllers, each local controller comprising a local hardware processor for each of a plurality of local wind turbines, and secondary non-transitive, computer-readable storage devices associated with the local hardware processors for storing instructions that, when executed by the local hardware processors, perform the step of calculating load sensitivities according to the disclosed method.

Fatigue load minimization in an operation of a wind farm

The present disclosure relates to a method and system for controlling an operation of a wind farm having a number of wind turbines by introducing a load sensitivity exchange signal and distributing optimization calculations for minimizing the fatigue load of the wind turbines.

Background of invention

Wind power is the fastest growing Renewable Energy Resource (RES). With the increasing penetration level, the variability and uncertainty of wind power have brought new technical challenges to the power system operation. The technical requirements for wind power integration are more stringent. This includes that the wind farm shall be capable of tracking the power reference from the grid provided by the system operator.

With the fast development of power electronics, the controllability of modern Wind Turbine Generators (WTGs) has been largely improved. When the required wind farm power is less than the maximum available power, the WTGs will limit the power production and operate at the derated mode.

The first dispatch schemes for the power references to the WTGs only focused on the power reference tracking. The power references in these systems were proportionally distributed to individual WTGs according to either the available power or the actual output power.

In recent studies, several multi-objective dispatch algorithms have been proposed. On top of providing the desired power production, the fatigue loads are minimized by coordination among WTGs. One known solution is to formulate the wind farm as a coupled, constrained multiple input and multiple output (MIMO) system. One problem with such an approach is that the order of such a system drastically grows with the increasing number of WTGs, which makes the system complex and unmanageable for real-time application.

If the formulated optimal problem is instead solved in a distributed manner, the computation burden at one place is reduced. However, in order to guarantee the optimality, iteration among the WTGs is required which introduces very demanding requirements on the communication speeds between parts of the system.

Summary of invention

The present disclosure relates to a method for controlling an operation of a wind farm connected to a grid, the wind farm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of:

- calculating a load sensitivity in the local controller of each wind turbine based on fluctuations of at least one fatigue load parameter of said wind turbine;
- providing an exchange signal between each of the local controllers and the central controller, said exchange signal comprising the calculated load sensitivity;
- solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines in the central controller based on the calculated load sensitivities of the wind turbines and power reference tracking provided by the grid, thereby providing local power references to each of the local controllers.

The proposed dispatch algorithm is suitable for real-time control of large-scale wind farms. The load sensitivity based optimal active power dispatch algorithm overcomes the problem of the known approaches of having either a centralized or a distributed approach by defining and introducing a measure of the sensitivity of fatigue loads of the wind turbines in relation to their power references. In this manner the sensitivity loads can be minimized while tracking the wind farm power reference. The formulation of the optimal dispatch algorithm for this purpose can be simplified without considering the high order wind farm model, and most computation tasks can be undertaken by the local controllers in the wind turbines. Expression of the load sensitivities are derived, which may significantly improve the calculation efficiency of the local controllers. Thus, according to the present disclosure, the optimal problem may be solved in a centralized manner while the computation burden in the central controller is largely reduced. In contrast to the known distributed schemes, no additional iterations are required.

The fatigue load of a wind turbine may comprise the load of the drive train due to the torsion of the shaft and the load of the tower structure due to the tower deflection in the wind turbine. Compared to the static loads, the dynamic stress causing the structural damage is typically a bigger issue of wind turbines. The load sensitivity exchange signal of the presently disclosed method for controlling an operation of a wind farm may indicate an expected fatigue load change as a result of the local power reference of the wind turbine. This information can be used in the central controller for solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines, and based on the solved optimal dispatch algorithm provide local power references to the local controllers. The step of solving an optimal dispatch algorithm for minimizing an overall fatigue load may comprise a minimization of the total shaft torque and thrust force variation for all wind turbines.

A control objective of the system typically also includes tracking power references from the system operator i.e. complying with power requirements, such as active power requirements, provided by the grid. Therefore, in one embodiment the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines comprises the step of complying with power reference requirements provided by the grid. The step of solving an optimal dispatch algorithm for minimizing an overall fatigue load may also comprise the step of minimizing a difference between a total generated power of all wind turbines and the power reference provided by the grid.

The present disclosure further relates to a system for controlling an operation of a wind farm connected to a grid, the system comprising:

- at least one central controller comprising a central hardware processor and at least a first non-transitive, computer-readable storage device for storing instructions that, when executed by the central hardware processor, causes the at least one central hardware processor to perform the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines according to presently disclosed method for controlling an operation of a wind farm connected to a grid, thereby providing local power references to each of the local controllers; and
- local controllers, each local controller comprising a local hardware processor for each of a plurality of local wind turbines, and secondary non-transitive, computer-readable storage devices associated with the local hardware processors for storing instructions that, when executed by the local hardware processors, perform the step of calculating load sensitivities

according to the presently disclosed method for controlling an operation of a wind farm connected to a grid.

The local controllers may comprise local communication units for communicating the calculated load sensitivities to the central controller. In one embodiment the local controllers are configured to communicate load sensitivities indicating expected fatigue load changes for each of the local wind turbines a result of the local power references to each of the wind turbines.The central controller may comprise a central communication unit for communicating local power references to each of the local controllers. The communication units may be adapted to use any suitable means of communication for communicating the exchange signals, including any wireless or wired communication. This applies in both directions, i.e. for the central and local controllers. Fig. 1 provides an example of the central controller (102) and local controllers (101) in relation to each other and in relation to the grid (103) and the wind turbines (104). The local controllers (101) provide load sensitivities (105) to the central controller (102) and the central controller provide local power references (106) to the local controllers (101).

Preferably in such a system there is a central processing unit configured to perform the steps of solving the optimal dispatch algorithm, and local processing units in the local controllers configured to perform the step of calculating load sensitivities.

Description of drawings

Fig. 1 shows a wind farm control structure according to the presently disclosed method and system for controlling an operation of a wind farm.

Fig. 2 shows a model of an individual wind turbine having a local controller.

Fig. 3 shows a first example of power reference tracking for a wind farm using a conventional proportionally distributed power reference approach and the presently disclosed optimal algorithm.

Fig. 4 shows fatigue load diagrams for the conventional algorithm and the presently disclosed optimal algorithm of the first example.

Fig. 5 shows a second example of power reference tracking for a wind farm using a conventional proportionally distributed power reference approach and the presently disclosed optimal algorithm.

Fig. 6 shows fatigue load diagrams for the conventional algorithm and the presently disclosed optimal algorithm of the second example.

Detailed description of the invention

The present disclosure relates to a method and a system for controlling an operation of a wind farm connected to a grid. The wind farm comprises a central controller and a plurality of wind turbines, each wind turbine having a local controller. The method introduces an exchange signal between the local controllers and the central controller, wherein said exchange signal comprises a calculated load sensitivity. The load sensitivity may be based on fluctuations of at least one fatigue load parameter the individual wind turbines. Preferably the central controller then solves an optimal dispatch algorithm to minimize an overall fatigue load of the wind turbines, wherein the problem formulation is based on the load sensitivities. The solving of the optimal dispatch algorithm may involve the provision of local power references to the local controllers. Preferably the central controller also takes into account the power reference tracking provided by the grid in the control of the local power references of the controllers.

An embodiment of a wind farm control structure according to the presently disclosed system and method is shown in fig. 1. The system comprises is a central controller and i local WTG controllers. Between the grid and the system controller there is a power reference P_{ref}^{wfc} from the grid, provided by the system operator, to the wind farm controller, and a total available power P_{avi}^{wfc} from the central controller to the grid. In contrast to the systems known in the art, the measurements of the WTGs (T_{g_ref}, θ_{ref}) are not sent to the central controller but to the local controllers where they are used to calculate the load sensitivities $\frac{\partial L}{\partial P_{ref}^{wt}}$. The local controllers may also provide power reference constraints $[P_{min}^{wt}, P_{max}^{wt}]$ of the individual WTGs. By solving an optimization problem, the central controller may provide power references $P_{ref}^{wt\_i}$ to the WTGs.

The method and system are suitable for real-time or substantially real-time control of a wind farm comprising a plurality of WTGs. The method and system may also be applied on large scale wind farms, such as in systems comprising more than 50, or more than 100, or more than 200 WTGs.

The present disclosure relates to a method for controlling the operation of a wind farm and system for performing the method. One embodiment of the system comprises a central processing unit configured to perform the steps of solving the optimal dispatch algorithm, and a number of local processing units in the local controllers configured to perform the step of calculating load sensitivities. In one embodiment the system comprises a first non-transitive, computer-readable storage device for storing instructions that, when executed by a processor, performs the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines. The system may further comprise secondary non-transitive, computer-readable storage devices for storing instructions that, when executed by a processor, performs the step of calculating load sensitivities in the local controllers. The secondary non-transitive, computer-readable storage devices may be placed in the local controllers.

The present disclosure further relates to a windfarm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, wherein the central and local controllers are configured to perform the presently disclosed method for controlling an operation of a wind.

Modelling and operation

The at least one fatigue load parameter of said wind turbine may a load of a drive train of each wind turbine. The at least one fatigue load parameter may also be related to an aerodynamic torque T_n and a thrust force F_t. The at least one fatigue load parameter may represent a measure of shaft torque fluctuations and/or thrust force fluctuations of each wind turbine. The at least one fatigue load parameter may also represent an internal structural load of the wind turbine. The fatigue load parameters may have a significant impact on the lifetime of the WTGs.

The fatigue load parameters may be based on a wind speed, and/or a pitch angle and/or a rotor generation speed of the wind turbine.

Fig. 2 shows a model of an individual wind turbine having a local controller. The local controller receives a local power reference P_{ref}^{wt} from the central controller. The WTG may further comprise parts for modelling a tower, aerodynamics, a pitch actuator, a drive train and a generator and may represent a variable speed pitch-controlled wind turbine.

The sampling time of the wind farm controller T_s may be in seconds. Therefore, the fast dynamics in the generator and pitch actuator may, as one option, be ignored. The oscillations in the shaft torsion and tower nodding may also be disregarded to reduce the model complexity. A simplified non-linear wind turbine model with a local control may be introduced, which is used to calculate the load sensitivities.

An aerodynamic torque T_a and thrust force F_t may be used as sources of nonlinearities, calculated by:

$$T_{\mathrm{a}} = \frac{0.5\pi\rho R^2 v_{\mathrm{r}}^3 C_{\mathrm{p}}(\lambda,\theta)}{\omega_{\mathrm{r}}},$$
$$F_{\mathrm{t}} = 0.5\rho R^2 v_{\mathrm{r}}^2 C_{\mathrm{t}}(\lambda,\theta),$$

where C_p and C_t are the power coefficient and thrust coefficient, respectively, R is the length of the blade, ρ is the air density, v_r is the effective wind speed on the rotor, and λ is the tip speed ratio, defined by $\lambda \triangleq \frac{\omega_r R}{v_r}$.

In the model the drive train is considered to be rigidly coupled and a single-mass model is used, where the rotor mass J_r and generator mass J_g are merged into one equivalent mass J_t, expressed by:

$$J_{\mathrm{t}} = J_{\mathrm{r}} + \eta_{\mathrm{g}}^2 J_{\mathrm{g}}.$$

According to the low-shaft motion equation

$$\dot{\omega}_{\mathrm{r}} = \frac{1}{J_{\mathrm{t}}}(T_{\mathrm{a}} - \eta_{\mathrm{g}} T_{\mathrm{g}}),$$
$$\omega_{\mathrm{g}} = \eta_{\mathrm{g}}\omega_{\mathrm{r}},$$

where ω_r and ω_t are the rotor and generator speed, respectively, and η_g is the gear box ratio.

In the torque control loop of the model, the vector control may be used to ensure a fast (in milliseconds) and accurate response. Since the dynamic is neglected, the generator torque T_g is approximately equal to its reference, i.e. $T_g \approx T_{g\_ref}$.

Load sensitivity

The load sensitivity may comprise one part corresponding to a load of the drive train due to torsion of the shaft and one part corresponding to the load of the tower structure due to tower deflection. The load sensitivity may be a dynamic load or a dynamic stress. Compared with static load, the dynamic stress causing the structural damage is typically a bigger issue for a WTG. In the presently disclosed method fluctuations of the shaft torque T_s and thrust force F_t may be damped, which reduces the related fatigue loads. The load sensitivities $\frac{\partial L}{\partial P_{ref}^{wt}}$ may therefore comprise components related to $\frac{\partial T_s}{\partial P_{ref}^{wt}}$ and $\frac{\partial F_t}{\partial P_{ref}^{wt}}$.

In one embodiment the load sensitivity indicates an expected fatigue load change as a result of the local power reference of the wind turbine or as a result of the actual generated power of the wind turbine. The following section describes how the load sensitivities may be calculated.

The time of the operating point may be t_0.The wind speed v_r may be estimated or measured. The measured power production, generator speed and pitch angle at t = t0 may be defined by P_{g0}, ω_{g0} and θ_0.

In a first step, equations of $\Delta\omega_g$ and $\Delta\theta$ may be derived:

$$\Delta\dot{\omega}_{\mathrm{g}} = \frac{\eta_{\mathrm{g}}}{J_{\mathrm{t}}}(\Delta T_{\mathrm{a}} - \eta_{\mathrm{g}}\Delta T_{\mathrm{g}}) + \frac{\eta_{\mathrm{g}}}{J_{\mathrm{t}}}(T_{\mathrm{a0}} - \eta_{\mathrm{g}}T_{\mathrm{g0}})$$

$$\Delta\dot{\theta} = \frac{K_{\mathrm{p}}}{K_{\mathrm{c0}}}\Delta\dot{\omega}_{\mathrm{g}} + \frac{K_{\mathrm{i}}}{K_{\mathrm{c0}}}(\omega_{\mathrm{g0}} + \Delta\omega_{\mathrm{g}} - \omega_{\mathrm{g\_rated}})$$

where $K_{c0} = f_c(P_{g0}, \theta_0)$.

One embodiment of the presently disclosed method for controlling an operation of a wind farm further comprises the step of calculating local pitch angle and/or generator torque references in the local controller of each wind turbine based on the local power reference for each controller.

In a second step, ΔT_n and ΔT_g , representing changes in the torque a certain point in time, can be calculated as:

$$\Delta T_{\mathrm{g}} \approx -\frac{P_{\mathrm{g}0}}{\omega_{\mathrm{g}0}^2}\Delta\omega_{\mathrm{g}} + \frac{1}{\omega_{\mathrm{g}0}}\Delta P_{\mathrm{ref}}^{\mathrm{wt}}.$$

$$\Delta T_{\mathrm{a}} \approx \frac{\partial T_{\mathrm{a}}}{\partial \omega_{\mathrm{g}}}\Big|_{(\omega_{\mathrm{g}0},v_{\mathrm{r}0},\theta_0)}\Delta\omega_{\mathrm{g}} + \frac{\partial T_{\mathrm{a}}}{\partial \theta}\Big|_{(\omega_{\mathrm{g}0},v_{\mathrm{r}0},\theta_0)}\Delta\theta$$

In a third step the partial derivatives of T_a then may be calculated as:

$$\frac{\partial T_{\mathrm{a}}}{\partial \omega_{\mathrm{g}}} = -\frac{\eta_{\mathrm{g}}P_0 C_{\mathrm{p}}(\omega_{\mathrm{g}0}, v_{\mathrm{r}0}, \theta_0)}{\omega_{\mathrm{g}0}^2} + \frac{\eta_{\mathrm{g}}P_0}{\omega_{\mathrm{g}0}}\frac{\partial C_{\mathrm{p}}(\omega_{\mathrm{g}}, v_{\mathrm{r}0}, \theta_0)}{\partial \omega_{\mathrm{g}}},$$

$$\frac{\partial T_{\mathrm{a}}}{\partial \theta} = \frac{\eta_{\mathrm{g}}P_0}{\omega_{\mathrm{g}0}}\frac{\partial C_{\mathrm{p}}(\omega_{\mathrm{g}0}, v_{\mathrm{r}0}, \theta)}{\partial \theta}.$$

wherein $P_0 \triangleq 0.5\Pi\rho R v_{r0}^3$. The nonlinear function C_p can be identified as a Piece-Wise Affine function.

Based on the calculations of ΔT_n and ΔT_g, the rotor mass and generator mass and gear box ratio, a first load sensitivity component $\frac{\partial T_s}{\partial P_{ref}^{wt}}$ may then be calculated as:

$$\frac{\partial T_{\mathrm{s}}}{\partial P_{\mathrm{ref}}^{\mathrm{wt}}} \approx \frac{\Delta T_{\mathrm{s}}}{\Delta P_{\mathrm{ref}}^{\mathrm{wt}}} = \underbrace{(\boldsymbol{C}_{\boldsymbol{T}_{\mathrm{s}}}\boldsymbol{B}_{\mathrm{d}} + \boldsymbol{D}_{\boldsymbol{T}_{\mathrm{s}}})}_{\text{Part 1}} + \underbrace{\frac{\boldsymbol{C}_{\boldsymbol{T}_{\mathrm{s}}}\boldsymbol{E}_{\mathrm{d}}}{\Delta P_{\mathrm{ref}}^{\mathrm{wt}}}}_{\text{Part 2}}$$

The derived load sensitivity first component may comprise two parts. A first part, part 1, is dependent only on the operating point. A second part, part 2, is dependent both on the operating point and the deviation of the power reference ΔP_{ref}^{wt} from the central controller to the local controller.

A second load sensitivity component $\frac{\partial F_t}{\partial P_{ref}^{wt}}$ may be calculated as:

$$\frac{\partial F_{\mathrm{t}}}{\partial P_{\mathrm{ref}}^{\mathrm{wt}}} \approx \frac{\Delta F_{\mathrm{t}}}{\Delta P_{\mathrm{ref}}^{\mathrm{wt}}} = \underbrace{\boldsymbol{C}_{\boldsymbol{F}_{\mathrm{t}}} \boldsymbol{B}_{\mathrm{d}}}_{\text{Part 1}} + \underbrace{\frac{\boldsymbol{C}_{\boldsymbol{F}_{\mathrm{t}}} \boldsymbol{E}_{\mathrm{d}}}{\Delta P_{\mathrm{ref}}^{\mathrm{wt}}}}_{\text{Part 2}}$$

The derived load sensitivity second component may comprise two parts. A first part, part 1, is a constant, dependent only on the operating point and the second part, part 2, is a variable, dependent both on the operating point and the deviation of the power reference ΔP_{ref}^{wt} from the central controller to the local controller.

Optimal dispatch problem

In order to minimize the overall fatigue load of the WTGs an optimal dispatch algorithm may be formulated and solved. For this purpose a first control objective of minimizing the fatigue loads of the WTGs may be introduced. Minimization of the fatigue loads of the WTGs may comprise minimization of T_s and F_t. A second control objective of tracking the power reference tracking provided by the grid, P_{ref}^{wfc} may also be used.

Therefore, in one embodiment of the presently disclosed method for controlling an operation of a wind farm, the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines comprises the step of complying with power reference requirements provided by the grid.

The step of solving an optimal dispatch algorithm for minimizing an overall fatigue load may further comprise the step of minimizing a difference between a total generated power of all wind turbines and the power reference provided by the grid.

For minimizing the overall fatigue load, a cost function may be introduced. If a wind farm comprises N_{wt} wind turbines a control vector u may be defined as:

$$u \triangleq [\Delta P_{\mathrm{ref}}^{\mathrm{wt\_1}}, \cdots, \Delta P_{\mathrm{ref}}^{\mathrm{wt\_}N_{\mathrm{wt}}}]', u \in \mathbb{R}^{N_{\mathrm{wt}} \times 1}$$

The optimization problem can then be formulated as:

$$\min_{u} \sum_{i=1}^{N_{\mathrm{wt}}} \| \frac{\partial T_{\mathrm{s}}^{i}}{\partial P_{\mathrm{ref}}^{\mathrm{wt\_}i}} u_i \|_{Q_{T_{\mathrm{s}}^{i}}}^{2} + \| \frac{\partial F_{\mathrm{t}}^{i}}{\partial P_{\mathrm{ref}}^{\mathrm{wt\_}i}} u_i \|_{Q_{F_{\mathrm{t}}^{i}}}^{2}$$

where $Q_{T_s}^{i}$ is a weighting factor which penalizes the variation Ts of the *i*th WTG, and $Q_{F_t}^{i}$ is the weighting factor which penalizes the variation of Ft of the *i*th WTG.

In one embodiment of the presently disclosed method the total shaft torque and thrust force variation comprises a weighting factor for each wind turbine. The step of solving an optimal dispatch algorithm for minimizing an overall fatigue load may therefore comprise minimization of a total shaft torque and thrust force variation for all wind turbines.

Other constraints that may be taken into account are the power reference tracking of the WTGs:

$$\sum_{i=1}^{N_{\mathrm{wt}}} u_i = P_{\mathrm{ref}}^{\mathrm{wfc}} - P^{\mathrm{wfc}}$$

and local constraints of $\Delta\theta$ and ΔT_g.For individual WTGs there may be incremental constraints in the local WTG controller. Based on the derived incremental state space model, these constraints can be equivalently transformed into the constraints of control variable u_i. A feasible range of u_i may also be sent to the central controller.

In one embodiment the exchange signal further comprises at least one physical limitation parameter of the wind turbine. The at least one physical limitation parameter comprises a power feasible operation range, and/or a generator torque range, and/or a pitch angle range.

A feasible operation range may be expressed as:

$$u \in [P_{\mathrm{min}}^{\mathrm{wt}}, P_{\mathrm{max}}^{\mathrm{wt}}]$$

wherein P_{min}^{wt} represents a minimum suitable power reference to the local controller and P_{max}^{wt} represents a maximum suitable power reference to the local controller.

Alternatively the local power references to each of the local controllers may represent upper limits of the power production of the individual wind turbines.

Examples

An example of a wind farm where the presently disclosed method has been implemented includes a wind farm comprising 10x5MW wind turbines.

In a first case, Case 1, the ramp rate limitation control was tested. Over a simulation time of 300 seconds the active power of the wind farm was observed. Fig. 3 shows a first example of power reference tracking for a wind farm using a conventional proportionally distributed power reference approach and the presently disclosed optimal algorithm. It can be observed that P^{wfc} of both algorithms follow the reference P_{ref}^{wfc} closely.

In the same case the fatigue loads were also observed. Only the fatigue load on the drive train was considered. The variations of T_s with the two algorithms are shown in fig. 4A. It can be observed that compared with CON (conventional proportional dispatch algorithm) (the power reference is proportionally distributed to individual WTGs), OPT (presently disclosed algorithm) reduces the variation of the shaft torque ΔT_s. The rainflow-counting algorithm is a known method for analysis of fatigue data in order to reduce a spectrum of varying stress into a set of simple stress reversals. In fig. 4B it is shown that less rainflow cycles are observed for the OPT method, which implies less fatigue load experienced by the wind turbine.

The Damage Equivalent Load (DEL), based on Miner's rule and dependent on materials properties specified by the slope of the S-N curve, may also be used to quantify the load minimization. Table 1 shows the calculated DELs for all wind turbines of the Case 1 setup.

No.	**v_{avr} (m/s)**	**DEL (CON) MNm**	**DEL (OPT) MNm**	**Percentage**
WT01	9.94	2.99	2.98	-0.34%
WT02	9.79	2.89	2.68	-7.84%

WT03	9.68	2.86	2.78	-2.88%
WT04	9.79	2.74	2.56	-7.03%
WT05	9.92	2.73	2.50	-9.20%
WT06	9.91	2.24	1.96	-14.29%
WT07	9.55	3.08	2.80	-10.00%
WT08	9.88	2.59	2.51	-3.19%
WT09	10.38	2.69	2.35	-14.47%
WT10	9.24	2.68	2.35	-14.35%
Summary		27.49	25.47	-7.35%

Table 1

In a second case, Case 2, a balance control scheme, wherein the wind farm production is reduced to specified constant level, is shown. In this case, balance control is applied i.e.:

$$P_{\mathrm{ref}}^{\mathrm{wfc}} = \begin{cases} 25\,\mathrm{MW} & \text{if } P_{\mathrm{ref}}^{\mathrm{wfc}} \leq P_{\mathrm{avi}}^{\mathrm{wfc}} \\ P_{\mathrm{avi}}^{\mathrm{wfc}} & \text{otherwise.} \end{cases}$$

Fig. 5 illustrates the available wind power P_{ref}^{wfc} and output power P_{avi}^{wfc} for both a conventional proportional dispatch algorithm (CON) and the presently disclosed method (OPT). It can be observed that P^{wfc} of both OPT and CON track the reference P_{ref}^{wfc} closely.

For the fatigue loads of the two approaches, fig. 6A shows the variations of T_s. The variation of the shaft torque ΔT_s is significantly reduced for the presently disclosed OPT approach. According to the cumulative rainflow cycles in fig. 6B less cycles are found for the OPT approach, which implies less fatigue loads experienced by the wind turbine.

The calculated DELs of all wind turbines are listed in Table 2.

No.	v_{avr}	DEL (CON)	DEL (OPT)	Percentage

	(m/s)	MNm	MNm	
WT01	9.94	2.18	1.77	-23.16%
WT02	9.79	1.91	1.20	-59.17%
WT03	9.68	2.30	1.52	-51.32%
WT04	9.79	2.01	1.10	-82.73%
WT05	9.92	1.99	1.61	-23.60%
WT06	9.91	1.81	1.55	-16.77%
WT07	9.55	2.06	1.40	-47.14%
WT08	9.88	2.21	1.54	-43.51%
WT09	10.38	2.61	2.24	-16.52%
WT10	9.24	1.81	1.47	-23.13%
Summary		20.89	15.40	-26.28%

Table 2

Further details of the invention

The invention will now be described in further detail with reference to the following items:

1. A method for controlling an operation of a wind farm connected to a grid, the wind farm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of:
   - calculating a load sensitivity in the local controller of each wind turbine based on fluctuations of at least one fatigue load parameter of said wind turbine;
   - providing an exchange signal between each of the local controllers and the central controller, said exchange signal comprising the calculated load sensitivity;
   - solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines in the central controller based on the calculated load sensitivities of the wind turbines and power reference tracking provided by the grid, thereby providing local power references to each of the local controllers.

2. The method according to any of the preceding items, wherein the at least one fatigue load parameter is a load of a drive train of each wind turbine

3. The method according to any of the preceding items, wherein the at least one fatigue load parameter is a measure of shaft torque fluctuations and/or thrust force fluctuations of each wind turbine.

4. The method according to any of the preceding items, wherein the at least one fatigue load parameter represents an internal structural load of the wind turbine.

5. The method according to any of the preceding items, wherein the at least one fatigue load parameter is based on a wind speed, and/or a pitch angle and/or a rotor generation speed of the wind turbine.

6. The method according to any of the preceding items, wherein the load sensitivity indicates an expected fatigue load change as a result of the local power reference of the wind turbine or as a result of the actual generated power of the wind turbine.

7. The method according to any of the preceding items, wherein the exchange signal further comprises at least one physical limitation parameter of the wind turbine.

8. The method according to item 7, wherein the at least one physical limitation parameter comprises a power feasible operation range, and/or a generator torque range, and/or a pitch angle range.

9. The method according to any of the preceding items, wherein the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load comprises minimization of a total shaft torque and thrust force variation for all wind turbines.

10. The method according to item 9, wherein the total shaft torque and thrust force variation comprises a weighting factor for each wind turbine.

11. The method according to any of the preceding items, wherein the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines comprises the step of complying with power reference requirements provided by the grid.

12. The method according to any of the preceding items, wherein the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load comprises the step of minimizing a difference between a total generated power of all wind turbines and the power reference provided by the grid.

13. The method according to any of the preceding items, wherein the local power references to each of the local controllers represent upper limits of the power production of the wind turbines.

14. The method according to any of the preceding items, further comprising the step of calculating local pitch angle and/or generator torque references in the local controller of each wind turbine based on the local power reference for each controller.

15. The method according to any of the preceding items, wherein the operation is substantially in real-time.

16. A system configured to perform the method according to any of items 1-15.

17. The system according to item 16 comprising a central processing unit configured to perform the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines and local processing units in the local controllers configured to perform the step of calculating load sensitivities in the local controllers.

18. A system of:
    - a first non-transitive, computer-readable storage device for storing instructions that, when executed by a processor, performs the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines according to the method according to any of items 1-15; and

- secondary non-transitive, computer-readable storage devices for storing instructions that, when executed by a processor, performs the step of calculating load sensitivities according to the method according to any of items 1-15.

19. A windfarm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, wherein the central and local controllers are configured to perform the method for controlling an operation of a wind farm according to any of items 1-15.

Claims

1. A method for controlling an operation of a wind farm connected to a grid, the wind farm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of:
   - calculating a load sensitivity in the local controller of each wind turbine based on fluctuations of at least one fatigue load parameter of said wind turbine;
   - providing an exchange signal between each of the local controllers and the central controller, said exchange signal comprising the calculated load sensitivity;
   - solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines in the central controller based on the calculated load sensitivities of the wind turbines and power reference tracking provided by the grid, thereby providing local power references to each of the local controllers.

2. The method according to any of the preceding claims, wherein the at least one fatigue load parameter is a load of a drive train of each wind turbine

3. The method according to any of the preceding claims, wherein the at least one fatigue load parameter is a measure of shaft torque fluctuations and/or thrust force fluctuations of each wind turbine.

4. The method according to any of the preceding claims, wherein the at least one fatigue load parameter is based on a wind speed, and/or a pitch angle and/or a rotor generation speed of the wind turbine.

5. The method according to any of the preceding claims, wherein the load sensitivity indicates an expected fatigue load change as a result of the local power reference of the wind turbine or as a result of the actual generated power of the wind turbine.

6. The method according to any of the preceding claims, wherein the exchange signal further comprises at least one physical limitation parameter of the wind turbine.

7. The method according to claim 6, wherein the at least one physical limitation parameter comprises a power feasible operation range, and/or a generator torque range, and/or a pitch angle range.

8. The method according to any of the preceding claims, wherein the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load comprises minimization of a total shaft torque and thrust force variation for all wind turbines.

9. The method according to claim 8, wherein the total shaft torque and thrust force variation comprises a weighting factor for each wind turbine.

10. The method according to any of the preceding claims, wherein the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines comprises the step of complying with power reference requirements provided by the grid.

11. The method according to any of the preceding claims, wherein the step of solving an optimal dispatch algorithm for minimizing an overall fatigue load comprises the step of minimizing a difference between a total generated power of all wind turbines and the power reference provided by the grid.

12. The method according to any of the preceding claims, further comprising the step of calculating local pitch angle and/or generator torque references in the local controller of each wind turbine based on the local power reference for each controller.

13. A system configured to perform the method according to any of claims 1-12.

14. A system for controlling an operation of a wind farm connected to a grid, the system comprising:
- at least one central controller comprising a central hardware processor and at least a first non-transitive, computer-readable storage device for storing instructions that, when executed by the central hardware processor, causes the at least one central hardware processor to perform the step of solving

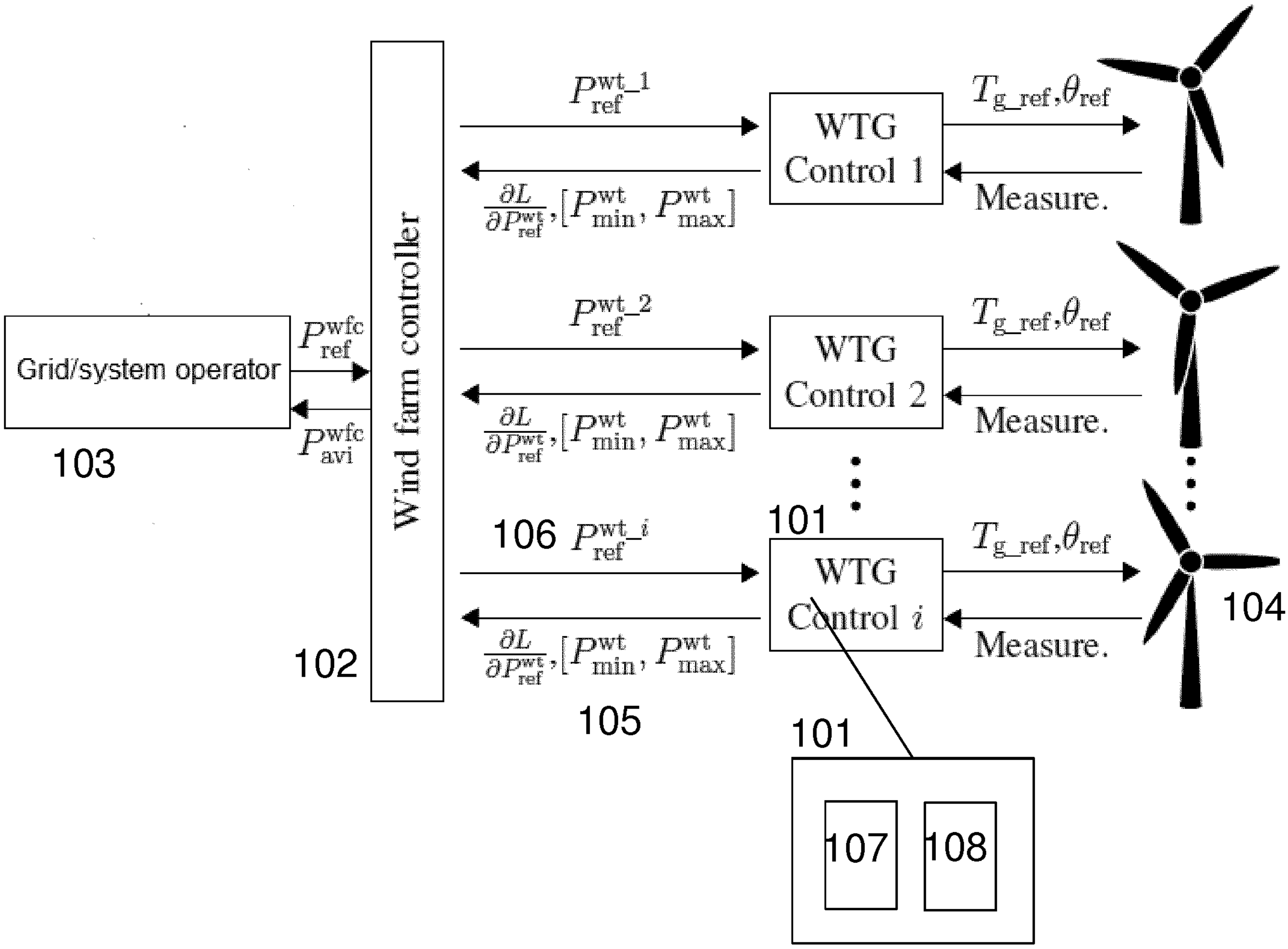
an optimal dispatch algorithm for minimizing an overall fatigue load of the wind turbines according to the method according to any of claims 1-12, thereby providing local power references to each of the local controllers; and

- local controllers, each local controller comprising a local hardware processor for each of a plurality of local wind turbines, and secondary non-transitive, computer-readable storage devices associated with the local hardware processors for storing instructions that, when executed by the local hardware processors, perform the step of calculating load sensitivities according to the method according to any of claims 1-12.

15. The system according to claim 14, wherein the local controllers comprise local communication units for communicating the calculated load sensitivities to the central controller, and wherein the central controller comprises a central communication unit for communicating local power references to each of the local controllers.

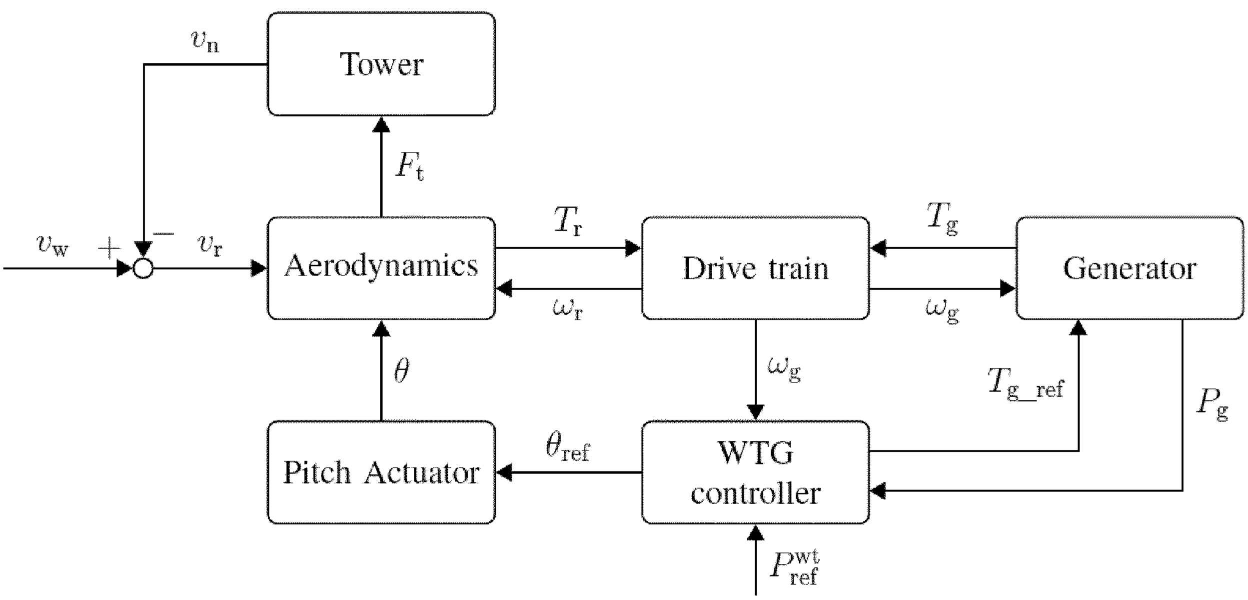
16. The system according to claim 15, wherein the load sensitivities indicate expected fatigue load changes for each of the local wind turbines a result of the local power references to each of the wind turbines.

17. A windfarm comprising a central controller and a plurality of wind turbines, each wind turbine having a local controller, wherein the central and local controllers are configured to perform the method for controlling an operation of a wind farm according to any of claims 1-12.



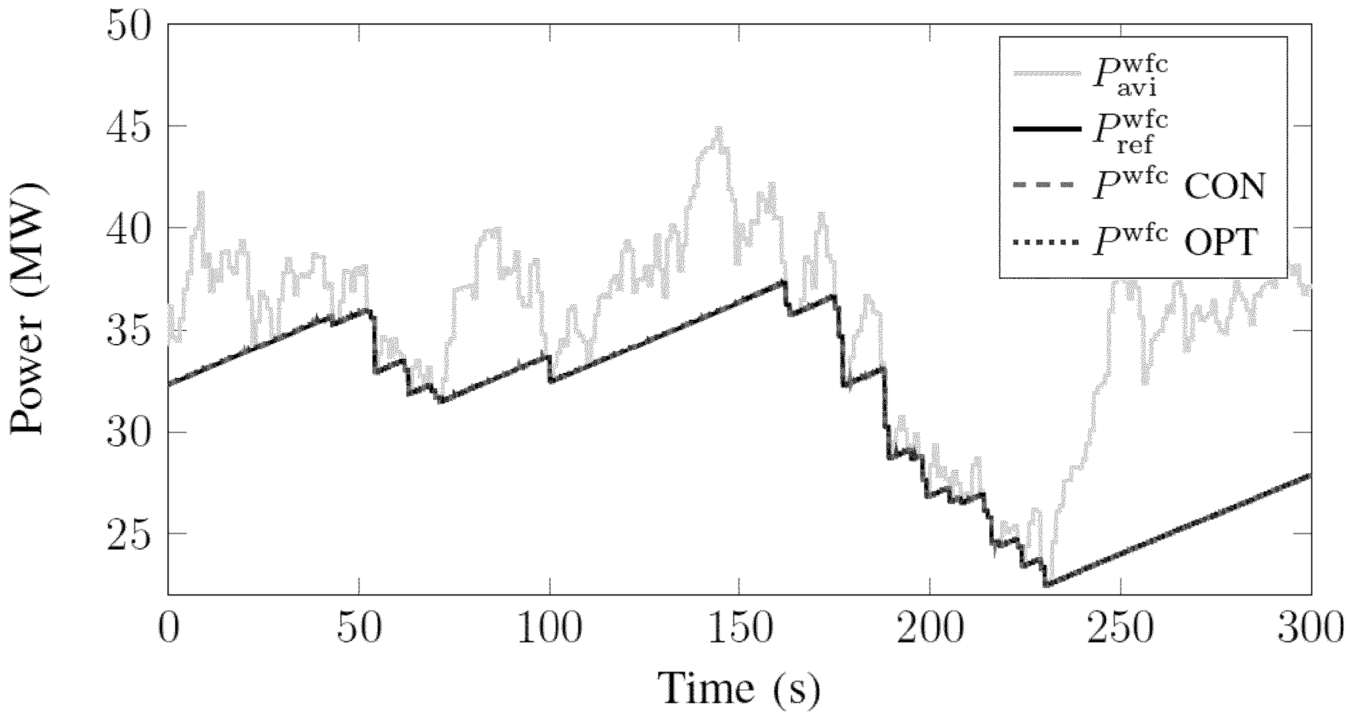
Grid/system operator
P_{ref}^{wfc}
P_{avi}^{wfc}
103
Wind farm controller
102
$P_{ref}^{wt\_1}$
$\frac{\partial L}{\partial P_{ref}^{wt}}, [P_{min}^{wt}, P_{max}^{wt}]$
WTG Control 1
T_{g_ref}, θ_{ref}
Measure.
$P_{ref}^{wt\_2}$
$\frac{\partial L}{\partial P_{ref}^{wt}}, [P_{min}^{wt}, P_{max}^{wt}]$
WTG Control 2
T_{g_ref}, θ_{ref}
Measure.
106 $P_{ref}^{wt\_i}$
$\frac{\partial L}{\partial P_{ref}^{wt}}, [P_{min}^{wt}, P_{max}^{wt}]$
105
101
WTG Control i
T_{g_ref}, θ_{ref}
Measure.
104
101
107
108

FIG. 1



v_n
Tower
F_t
v_w
+
−
v_r
Aerodynamics
T_r
ω_r
Drive train
T_g
ω_g
Generator
θ
ω_g
T_{g_ref}
P_g
Pitch Actuator
θ_{ref}
WTG controller
P_{ref}^{wt}

FIG. 2



50
45
40
35
30
25
Power (MW)
0
50
100
150
200
250
300
Time (s)
$P_{\text{avi}}^{\text{wfc}}$
$P_{\text{ref}}^{\text{wfc}}$
P^{wfc} CON
P^{wfc} OPT

FIG. 3

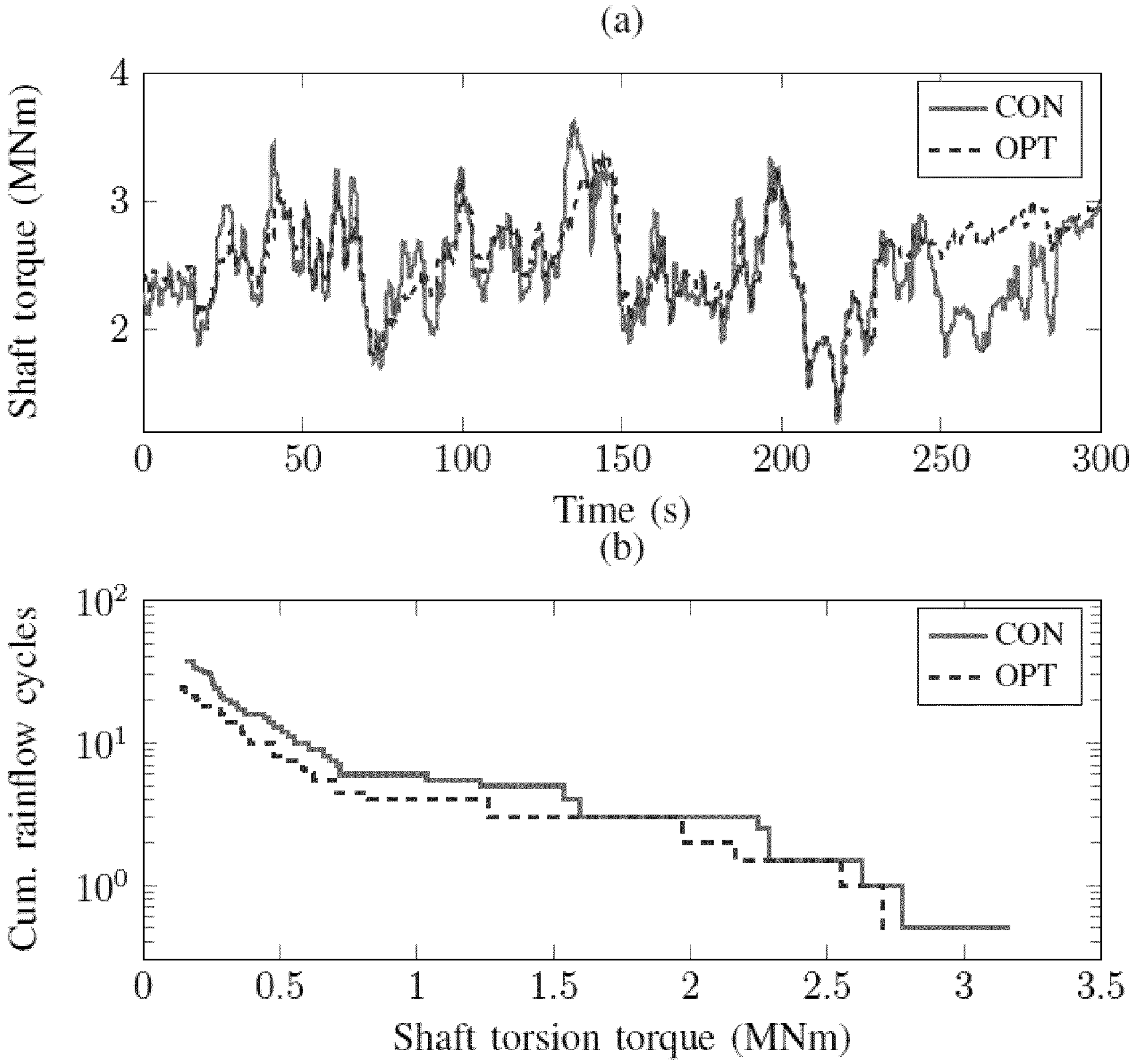
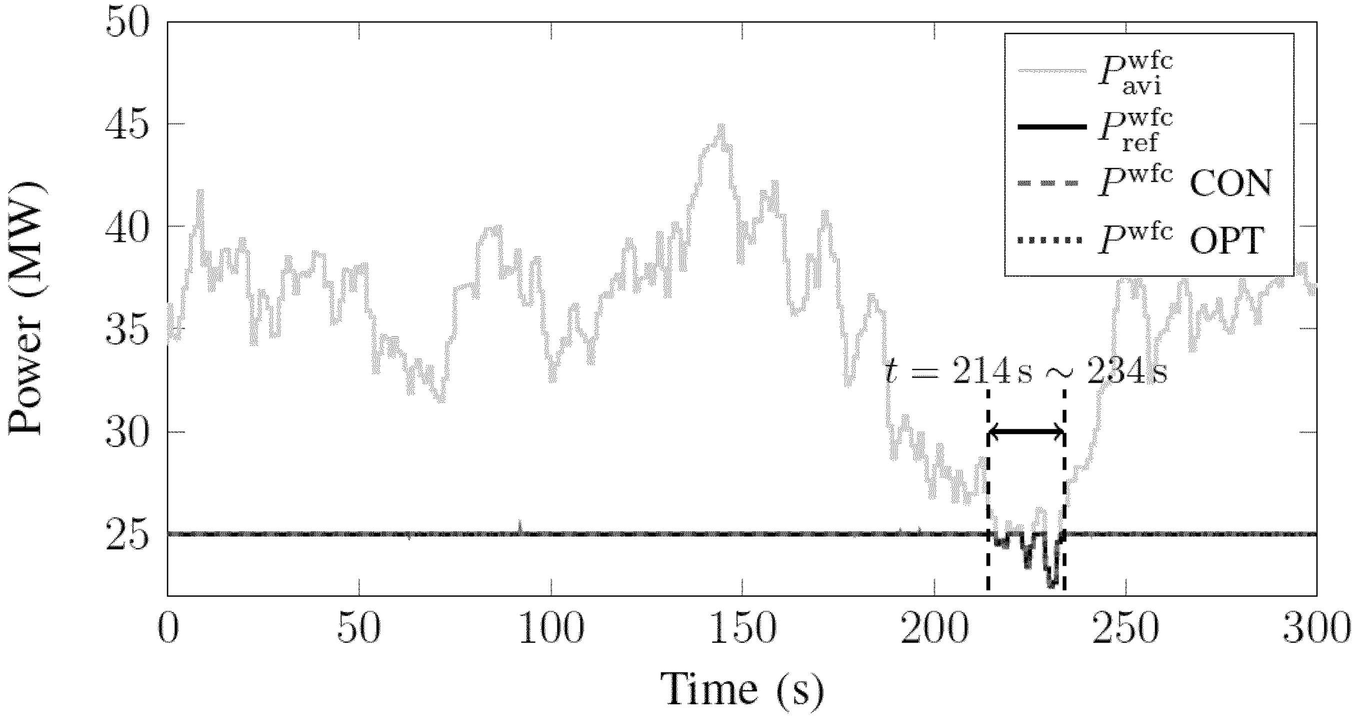

(a)
4
3
2
Shaft torque (MNm)
0
50
100
150
200
250
300
Time (s)
CON
OPT
(b)
10^2
10^1
10^0
Cum. rainflow cycles
0
0.5
1
1.5
2
2.5
3
3.5
Shaft torsion torque (MNm)
CON
OPT

FIG. 4



50
45
40
35
30
25
0
50
100
150
200
250
300
Power (MW)
Time (s)
$P_{\text{avi}}^{\text{wfc}}$
$P_{\text{ref}}^{\text{wfc}}$
P^{wfc} CON
P^{wfc} OPT
$t = 214\,\text{s} \sim 234\,\text{s}$

FIG. 5

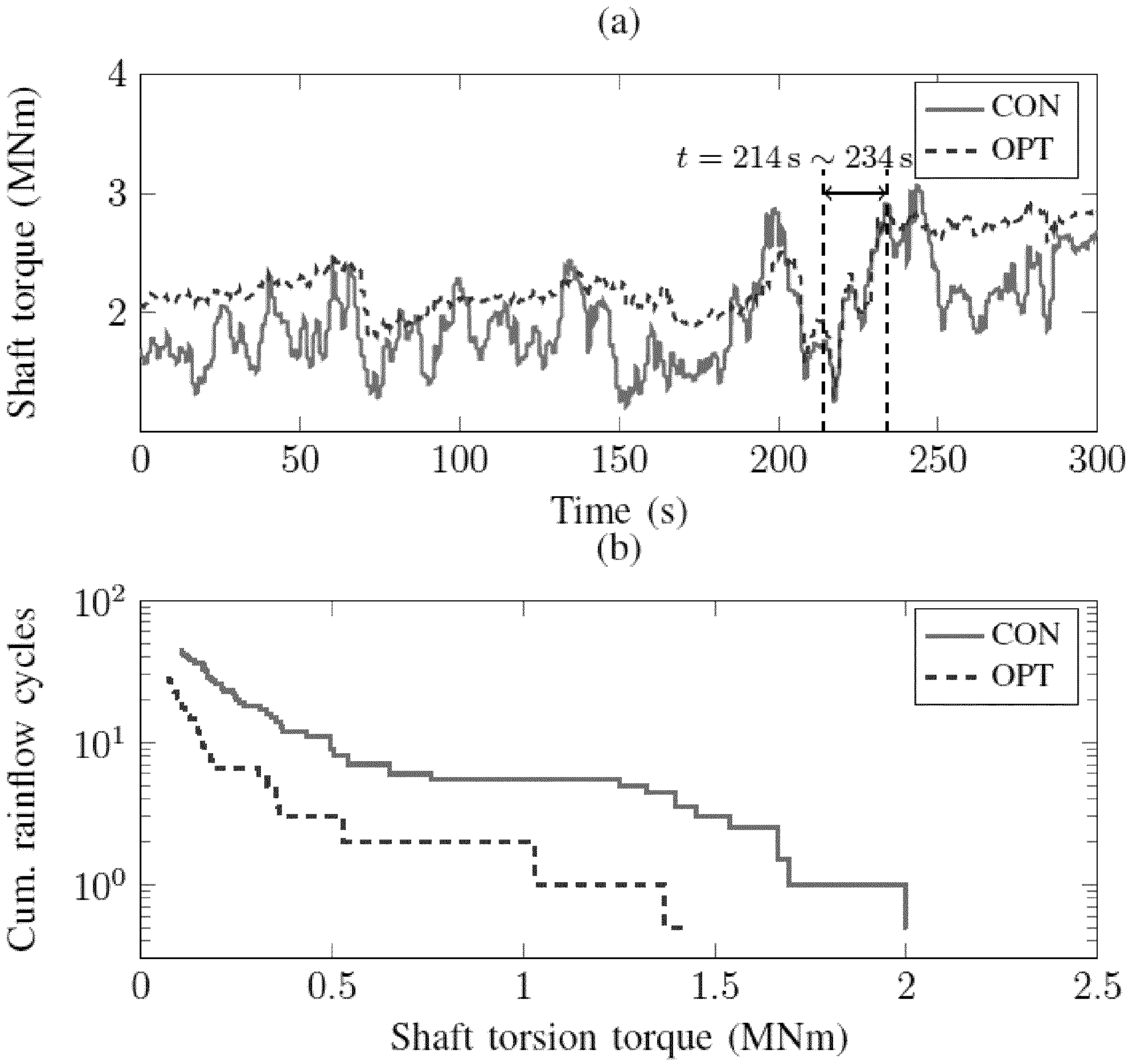

(a)
Shaft torque (MNm)
4
3
2
CON
OPT
$t = 214\,\mathrm{s} \sim 234\,\mathrm{s}$
0
50
100
150
200
250
300
Time (s)
(b)
Cum. rainflow cycles
10^2
10^1
10^0
CON
OPT
0
0.5
1
1.5
2
2.5
Shaft torsion torque (MNm)

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/084350

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06Q10/00 G06Q50/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016/333854 A1 (LUND ARNOLD M [US] ET AL) 17 November 2016 (2016-11-17) paragraph [0032] - paragraph [0039] paragraph [0043] - paragraph [0044] figures 2,3 The intelligent wind turbines 202 may be any suitable wind turbine as described herein (e.g. FIG. 1) and may also include sophisticated sensors (e.g. 216, 218) and processing capabilities in-built with the turbine for the SCADA system to collect data from and stream back to the cloud. Further, the SCADA system 32 is configured to provide on-site communications for operators to be able to retrieve data from turbines and/or to interact with the control system.; paragraph [0046] - paragraph [0048]; figure 4	1-17

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 January 2018	06/02/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Anastasov, Yuliyan

1

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/084350

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.

X	WO 2013/044925 A1 (VESTAS WIND SYS AS [DK]) 4 April 2013 (2013-04-04) the whole document	1-17

1

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/084350

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		EP 2766600 A1	20-08-2014
		US 2014248123 A1	04-09-2014
		WO 2013044925 A1	04-04-2013